Tracer gauge: An automated dye dilution gauging system for ice-affected streams

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[1] In-stream flow protection programs require accurate, real-time streamflow data to aid in the protection of aquatic ecosystems during winter base flow periods. In cold regions, however, winter streamflow often can only be estimated because in-channel ice causes variable backwater conditions and alters the stage-discharge relation. In this study, an automated dye dilution gauging system, a tracer gauge, was developed for measuring discharge in ice-affected streams. Rhodamine WT is injected into the stream at a constant rate, and downstream concentrations are measured with a submersible fluorometer. Data loggers control system operations, monitor key variables, and perform discharge calculations. Comparison of discharge from the tracer gauge and from a Cipoletti weir during periods of extensive ice cover indicated that the root-mean-square error of the tracer gauge was 0.029 m^3 s^{-1}, or 6.3% of average discharge for the study period. The tracer gauge system can provide much more accurate data than is currently available for streams that are strongly ice affected and, thus, could substantially improve management of in-stream flow protection programs during winter in cold regions. Care must be taken, however, to test for the validity of key assumptions, including complete mixing and conservative behavior of dye, no changes in storage, and no gains or losses of water to or from the stream along the study reach. These assumptions may be tested by measuring flow-weighted dye concentrations across the stream, performing dye mass balance analyses, and evaluating breakthrough curve behavior.

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1. Introduction

[2] During winter in cold regions of the world, ice and snow can partially fill stream channels, altering channel morphology, and create varying backwater conditions (Figure 1) [*Capesius et al.*, 2005]. These conditions change the stage-discharge relation, leading to inaccuracies in discharge values calculated using continuous stage records and rating equations. As a result, discharge often is estimated during winter in cold regions from relatively infrequent velocity-area discharge measurements [*Rantz et al.*, 1982].

[3] The uncertainty in winter streamflow records has important implications for aquatic ecosystems, which may be adversely affected if streamflow drops below the amount needed to maintain suitable dissolved oxygen and chemical conditions. In many mountain streams in cold regions, native streamflow tends to decline through the fall and winter as the subsurface reservoir drains and because most precipitation is stored in seasonal snowpacks. Water diversions can reduce flows below those necessary to sustain aquatic life. Eight states in the western United States have in-stream flow protection programs that specify minimum flows to protect fisheries and aquatic habitats [*McKinney and Taylor*, 1988]. The state of Colorado, for example, has an in-stream flow rights program that protects 13,600 km of streams in the state (http://cwcb.state.co.us/streamandlake; accessed 1 April 2008) (D. Merriman and A. M. Janicki, Colorado's instream flow program—How it works and why it's good for Colorado, 2005, Colorado Water Conservation Board, available at http://cwcb.state.co.us/NR/rdonlyres/6333F3FC-E2F8-4E7E-9BD3-690FCC4285D1/0/FinalRiparianAssocPaper.pdf). State agencies have developed a low-flow alert system to notify staff if flows drop below specified amounts on protected reaches. During winter, however, the flow alert system is of limited utility because real-time streamflow data are seldom available. There is a need for accurate, real-time streamflow data during winter to aid state agencies in protection of aquatic ecosystems. Provinces and countries in other cold regions of the world have similar needs [*McKinney and Taylor*, 1988].

[4] In theory, manual discharge measurements could be made frequently (e.g., daily) using standard velocity-area methods to provide the required winter streamflow data. This frequency, however, would be prohibitively expensive and would subject field technicians to unnecessary risks associated with hazardous winter driving conditions and working in ice-affected streams.

[5] The constant-rate tracer dilution method of measuring discharge is an alternative to the commonly used velocity-area method [*Kilpatrick and Cobb*, 1985], and it has strong potential for improving the accuracy of winter discharge measurements. The method relies on the principle of con-

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Figure 1. Photograph of ice in channel at Bear Creek, near Morrison, Colorado, during typical midwinter ice conditions (25 February 2003).

servation of mass. If a tracer of known concentration is injected into a stream at a constant rate, it will be diluted by an amount that is proportional to the discharge of the stream [*Kilpatrick and Cobb*, 1985]. This may be expressed as a mass balance equation:

$$Q_{\mathrm{upstream}}C_{\mathrm{upstream}} + Q_{\mathrm{injection}}C_{\mathrm{injection}} = Q_{\mathrm{downstream}}C_{\mathrm{downstream}}, \quad (1)$$

where Q is stream discharge or the injection rate and C is the tracer concentration. The injection rate is several orders of magnitude smaller than the discharge in the stream, so the equation may be simplified and rearranged to solve for stream discharge (Q):

$$Q = Q_{\mathrm{injection}}C_{\mathrm{injection}}/(C_{\mathrm{plateau}} - C_{\mathrm{background}}), \quad (2)$$

where $C_{\mathrm{background}} = C_{\mathrm{upstream}}$ and $C_{\mathrm{plateau}} = C_{\mathrm{downstream}}$. The equation is valid after tracer concentrations have reached a stable plateau (steady state). Key assumptions when using the tracer dilution method include (1) the tracer is conservative, (2) there is complete mixing of the tracer in the stream at the downstream measurement site, (3) there is no change in storage, and (4) there are no gains or losses of water along the measurement reach of the stream. Ideally, in constant-rate injections, tracer concentrations at the downstream site have a low background value, increase quickly after the injection begins until they reach a stable plateau, and then decrease quickly to background concentrations after the injection stops. Tracers that have low background concentrations and are easily measured are preferred; commonly used tracers include salts and fluorescent dyes [*Kilpatrick and Cobb*, 1985].

[6] Rhodamine WT (RWT) was developed for water-tracing applications and is one of the most commonly used dyes for that purpose. It has low toxicity, low background concentrations, and high diffusivity [*Kilpatrick and Wilson*, 1989; *Smart and Laidlaw*, 1977; *Smart*, 1982; *Wilson et al.*, 1986]. It has two isomers with different sorption characteristics [*Vasudevan et al.*, 2001] but adsorbs only slightly on sediments, except in acidic streams; other tracers need to be used in streams with low pH, such as in acid mine drainage areas [*Bencala et al.*, 1983; *Smart and Laidlaw*, 1977]. Detailed information on the constant-rate tracer dilution method and a description of a simple constant-rate injection system are available in the work by *Kilpatrick and Cobb* [1985].

[7] One of the first automated tracer dilution discharge systems was used in Wisconsin to measure flow in storm drainage systems [*Duerk*, 1983]. A stage-activated peristaltic pump was used to inject RWT into the stream, and samples were collected downstream using an automated water sampler (autosampler). Comparison to discharge calculated from a rating equation indicated that the tracer dilution discharge measurements were accurate to within 10%. A similar system was developed to measure discharge in small streams in Iowa, but it used a metering pump, providing increased accuracy by maintaining a more constant injection rate [*Soenksen*, 1990].

[8] Automated tracer dilution discharge measurements in subfreezing conditions have worked with limited success. A system tested in the Northwest Territories in Canada during springtime used a continuously operating metering pump to inject RWT into a snow-filled stream channel and an autosampler to collect samples downstream [*Russell et al.*, 2004]. Poor recovery of the dye limited the accuracy of the system. Adding salt to the solution depressed its freezing point to $-4°$C, but freezing continued to be a problem at lower temperatures.

[9] Although suitable during springtime when air temperatures are not far below 0°C, salt solutions do not provide adequate freezing protection in the central Rocky Mountains during midwinter, when temperatures sometimes drop below $-25°$C. In a test of a tracer dilution system in Colorado during winter 2002, an approximately 100,000 mg L^{-1} sodium chloride solution was injected into a stream using a metering pump [*Capesius et al.*, 2005]. Despite the strength of the salt solution, partial freezing caused substantial problems in system operation.

[10] The objective of this study was to develop a tracer dilution discharge measurement system that was automated, reliable, and accurate at temperatures as low as $-25°$C and provided real-time data. This paper describes such a system and provides a discussion of test results and system limitations.

2. Methods

2.1. Description of System

[11] The automated system that was developed in this study, the tracer gauge, consisted of equipment at two sites separated by enough distance to allow for complete mixing of the tracer in the stream. Data loggers at both sites collected data from sensors, performed calculations, and controlled system operations (e.g., electronic valves, an

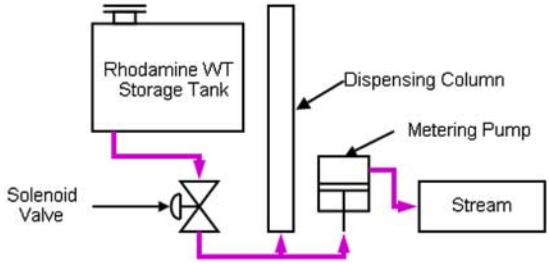

Figure 2. Diagram of tracer gauge dye injection system.

injection pump, and telemetry [*Fleming*, 2008]). The entire system operated on 12-V direct current power, which was supplied by solar panels and batteries.

[12] At the upstream site, RWT solution was injected into the stream three times per day for 60 min at a constant rate using a low-speed metering pump. The pump drew solution from a 2.85-cm-diameter column that had a high-precision pressure transducer at the bottom to measure head; the injection rate was calculated from the drop in head in the dispensing column during the injection cycle. The solution in the column was replenished after each measurement by temporarily opening a solenoid valve, which allowed solution to flow into the column by gravity from a large storage tank (Figure 2). By drawing solution from a small-diameter column rather than directly from the storage tank, the injection rate could be calculated more accurately because the change in head per unit volume of solution was greater.

[13] At the downstream site, a submersible fluorometer measured in-stream RWT concentrations, and the data were relayed to the upstream site via radiotelemetry. Discharge was calculated by the upstream data logger using equation (2). Four values were required for the calculation: (1) injection rate ($Q_{\mathrm{injection}}$), (2) background concentration ($C_{\mathrm{background}}$), (3) plateau concentration (C_{plateau}), and (4) injected tracer concentration ($C_{\mathrm{injection}}$).

[14] Injection rate was measured by the upstream equipment, background concentration was the minimum RWT concentration measured in the stream site prior to the injection, and plateau concentration was the maximum RWT concentration measured at the downstream site during the injection after concentrations had stabilized. The injected tracer concentration was the RWT concentration of the injection solution, as determined by the solution recipe.

[15] After discharge was calculated, it was transmitted via satellite to a web server, providing real-time data via the Internet (http://co.water.usgs.gov/watershed/fraserriver/tracergauge/index.html; accessed 5 April 2008). A detailed description of the system is available in the work by *Fleming* [2008].

[16] To prevent the injection solution from freezing, propylene glycol, which is a nontoxic antifreeze and common food additive, was added to the solution. The injection solution consisted of 15 mg L^{-1} RWT in a 1:1 mixture of propylene glycol and deionized water. Comparison of standards made with and without propylene glycol indicated that propylene glycol did not significantly alter RWT fluorescence. The solution remains liquid well below $-25°C$; however, its viscosity is inversely related to temperature, and it becomes increasingly difficult to pump as the temperature declines. To minimize this problem, the valves, the pump, the tank that contained the injection solution, and most plumbing lines were housed in an insulated enclosure that was maintained at temperatures above $-10°C$ by a thermostatically controlled thermoelectric heater. Plumbing lines that ran from the equipment housing to the stream were buried to insulate them from the cold. A power consumption analysis for the tracer gauge system indicated that the upstream site requires up to 10.9 A h of energy per day depending on air temperatures, with the heater consuming most of the power. The downstream site required 1.85 A h per day.

[17] Variations in battery voltage are a common problem in constant-rate dye dilution discharge measurements. As batteries are drawn down over the course of an injection cycle, the injection rate declines, potentially leading to errors in calculated discharge. To minimize voltage variations to the pump, a 5-A step-down voltage regulator was placed in line between the batteries and the pump; the regulator damped voltage changes by 87% (1.5-V input change = 0.2-V output change).

[18] Another possible source of error in calculated discharge is variations in injection solution concentration, which can vary between batches. An automatic sampler was used to obtain samples of the injection solution at a regular time interval set by the user (e.g., 1–3 days). The automatic sampler consisted of a series of solenoid valves, which were controlled by a 16-channel relay connected to the data logger. When a valve opened, solution flowed by gravity from the dispensing column into a 15-mL glass vial. Samples were analyzed in the laboratory using a fluorometer to verify the solution concentrations.

[19] The data logger program recorded key diagnostic parameters of system operation. If problems arose, the data logger assigned a value of -9 to discharge and output an error code that was used to troubleshoot the system [*Fleming*, 2008]. The error codes were included in the telemetered data, providing automated error detection.

2.2. System Testing

2.2.1. Site Descriptions

[20] The tracer gauge was developed and tested during the winters of 2003–2007. Initial testing was performed during 2003–2004 at Bear Creek in Morrison, Colorado (Figure 1 and Table 1). Bear Creek is a small mountain stream with winter flows that typically range from 0.14 to 0.71 $m^3\ s^{-1}$ (5 to 25 $ft^3\ s^{-1}$) (http://www.dwr.state.co.us/SurfaceWater/Default.aspx; accessed 8 July 2008). The site was selected because there is a stream gauge with a Cipoletti weir, which provided accurate low-flow discharge data for comparison with the tracer gauge [*Rantz et al.*, 1982]. The study reach also has a minimum in-stream flow requirement of 0.14 $m^3\ s^{-1}$ (5 $ft^3\ s^{-1}$) to protect fisheries and aquatic habitat (http://cwcb.state.co.us/streamandlake; accessed 1 April 2008). Average daily minimum January temperatures at Bear Creek are $-8°C$ (http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?co4452; accessed 30 March 2008). Although substantial ice cover is common at Bear Creek during winter, the weir is seldom affected by ice because of high flow velocities through the throat (Figure 1). Two identical submersible RWT sensors were installed at Bear Creek at one third and two thirds of the distance across the stream. The purpose of having two sensors was to minimize the potential effects of inadequate mixing, which was a concern because the separation dis-

Table 1. Station Information

Station Number	Station Name	Station Location		Elevation (m)	Operating Agency
		Latitude	Longitude		
06710500	Bear Creek at Morrison, Colorado	39°39′11″	105°11′43″	2609	Colorado Division of Water Resources
09024000	Fraser River at Winter Park, Colorado	39°54′00″	104°46′34″	2715	U.S. Geological Survey

tance between the upper and lower sites (60 m) was limited by land ownership. Stage in the pool above the Cipoletti weir was measured using a submersible pressure transducer.

[21] Additional testing and refinement of the tracer gauge was performed on the Fraser River at Winter Park, Colorado, during 2005–2006 to evaluate performance and reliability under colder climate conditions (Table 1). The tracer gauge was operated as a real-time stream gauge at the Fraser River site during the winter of 2007. The town of Fraser, 10 km north of the Fraser River gauge, has an average daily minimum temperature of −21°C during January (http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?co3113; accessed 30 March 2008), and the stream typically is 95–100% ice covered during winter. The U.S. Geological Survey (USGS) operates a stream gauge at the Fraser River site with a float-stilling well system, but discharge is estimated for most of the winter because of severe ice conditions. Manual velocity-area discharge measurements indicate that winter flows typically range from 0.08 to 0.28 $m^3 s^{-1}$ (3 to 10 $ft^3 s^{-1}$). There is a minimum in-stream flow requirement of 0.10 $m^3 s^{-1}$ (3.5 $ft^3 s^{-1}$) along the study reach, which was 317 m in length.

2.2.2. Dye Injection System

[22] The injection rate is a key variable in the discharge calculation (equation (2)). A constant rate of injection is required to establish steady state concentrations of dye in the stream. Variations in injection rate were evaluated on the basis of the decrease in head in the dispensing column during and among injection cycles.

[23] The length of the injection cycle may be adjusted by changing parameters in the data logger program. Selection of an appropriate length for the injection cycle is based on the need to obtain suitable characteristics for the RWT concentration plateau and background, which is discussed in more detail in section 3.

2.2.3. Rhodamine WT Measurements

[24] Three submersible RWT measurement systems with optical sensors were tested in this study, including the Cyclops-7, which is a stand-alone RWT sensor manufactured and sold by Turner Designs, and two sonde and sensor systems sold by Hach Environmental and YSI Environmental (any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government).

[25] Fouling of sensor optics by biofilms will gradually reduce the fluorescence signal unless the optics are cleaned frequently. The Hach and YSI sondes have wipers that clean the optics at user-specified intervals. The Cyclops-7 does not have an integrated wiper, but for this study an automated wiper system was added to prevent fouling.

2.2.4. Tests for Adequacy of Mixing and Conservative Behavior of Tracer

[26] One of the key assumptions in tracer dilution discharge measurements is that the tracer is completely mixed by the time it reaches the downstream sampling site. Incomplete mixing can cause errors in the discharge calculation because of variations in RWT concentration across the stream. If the RWT sensor is in a location where concentrations are lower than average for a given cross section, the calculated discharge will be too high. The opposite occurs if the sensor is located where concentrations are higher than average for the cross section.

[27] Usually, the degree of mixing increases in the downstream direction until it is complete, which is referred to as the mixing length [*Rantz et al.*, 1982]. Mixing length should be carefully considered when evaluating the appropriate separation distance between the injection and measurement sites in a tracer gauge system. A variety of equations have been proposed to estimate mixing length on the basis of average stream width, depth, and velocity, and in some cases streambed roughness. Ideally, each of the parameters used in the equations would be measured in the field, but often most are estimated because the measurements are labor intensive. It should be noted that mixing length may vary depending on streamflow and icing conditions in the stream [*Beltaos*, 1998].

[28] Mixing length was estimated for the Bear Creek and Fraser River sites using the equations by *Day* [1977], *Engmann and Kellerhals* [1974], *Rantz et al.* [1982], and *Ward* [1973]. Average stream width, depth, and velocity were measured at Bear Creek and the Fraser River at flows of 0.17 $m^3 s^{-1}$ (6.00 $ft^3 s^{-1}$) and 0.16 $m^3 s^{-1}$ (5.65 $ft^3 s^{-1}$), respectively.

[29] Actual mixing was evaluated for both sites by measuring RWT concentrations in cross sections at the downstream instrumentation sites under varying ice conditions. Within the cross sections, five samples were collected in equal-width increments across the stream. The cross-section measurements were performed twice at Bear Creek in 2004 and four times at the Fraser River in 2006.

[30] Cross-section measurements of RWT concentrations provide a qualitative assessment of mixing. A quantitative assessment requires combining these data with independent discharge measurements (e.g., using the velocity-area method) at each sampling location within a cross section to calculate a flow-weighted mean RWT concentration [*Rantz et al.*, 1982]. This was done for each of the four cross-section sampling events at the downstream Fraser River site in 2006. Analogous measurements were made on 20 October 2007 at six cross-section locations along a longitudinal transect in the Fraser River study reach to quantify actual mixing length.

[31] Conservative behavior of the tracer is another important assumption in tracer dilution discharge measurements. Although RWT adsorbs only slightly on sediments in nonacidic streams, adsorption can become significant if study reaches are long or sediment concentrations are high [*Bencala et al.*, 1983; *Rantz et al.*, 1982; *Russell et al.*, 2004]. RWT also can be lost though chemical decay if free

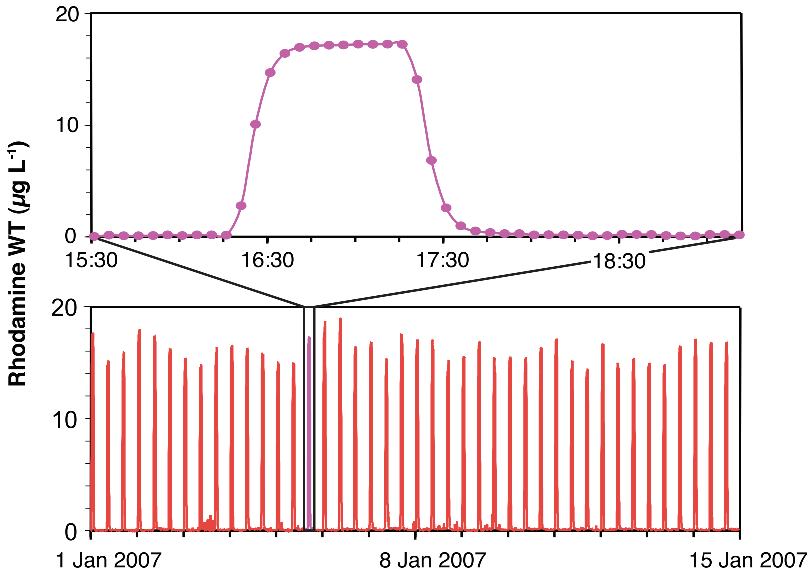

Figure 3. Bottom plot shows Rhodamine WT concentrations in Fraser River, early January 2007 (95–100% ice cover). Top plot shows expanded view from injection on the afternoon of 5 January 2007.

chlorine is present, but this is unlikely to be a problem except in areas immediately downstream from water treatment facilities [*Smart and Laidlaw*, 1977]. In addition, dye can be lost to the subsurface along losing reaches of streams.

[32] Dye loss can be evaluated by performing a mass balance analysis using data from cross-sectional concentration and discharge measurements. One difficulty with this approach is that velocity-area discharge measurements in mountain streams often can have high uncertainty because of streambed roughness, and during winter the problem may be compounded by in-channel ice.

2.2.5. Comparison With Reference Discharge Values

[33] Evaluating the overall accuracy of the tracer gauge system requires independent, high-quality discharge data for comparison. Bear Creek was selected as the initial site for testing of the tracer gauge because it had a Cipoletti weir that remained free of ice even when the channel was mostly ice covered, providing an accurate low-flow discharge record.

[34] Tracer gauge discharge values were compared to 15-min average discharge values from the Cipoletti weir at Bear Creek during 2003 and 2004 (http://www.dwr.state.co.us/SurfaceWater/Default.aspx; accessed 8 July 2008). Although Bear Creek had extensive ice cover during the study period, the weir remained ice free because of high flow velocities through the throat. Independent, high-quality discharge data were not available for the Fraser River, precluding a comparison of discharge values from the tracer gauge and a reference data set. A 1.22-m (4-ft) noncontracting weir was installed at the Fraser River site during 2006; however, it was strongly affected by ice, and the data were not considered useable.

3. Results and Discussion

3.1. Plateau Characteristics

[35] It is important that tracer concentrations reach a stable plateau when performing constant-rate tracer dilution discharge measurements. A high signal to noise ratio (plateau RWT:background RWT) is desirable, but this needs to be balanced with the requirement that RWT concentrations remain below 10 μg L^{-1} at drinking water intakes (primarily for aesthetic reasons) [*Field et al.*, 1995; *Schneider*, 1986].

[36] The length of the dye injection cycle was selected on the basis of observed traveltime and behavior of RWT concentrations during and between plateaus. During the winters of 2006–2007, the tracer gauge injected RWT into the stream for 60 min at the beginning of each 8-h period. Typically, stream water RWT concentrations increased quickly from background, reached a stable plateau, and then declined quickly after the end of the injection cycle (Figure 3). Plateau concentrations varied with discharge, typically ranging from 14 to 18 μg L^{-1} at the downstream instrumentation site, but were well below 10 μg L^{-1} at the nearest drinking water intake. Background fluorescence readings typically were less than 1 μg L^{-1}, but slightly elevated background readings occurred on several occasions, such as on 3 January 2007 (Figure 3). The observed variability in background fluorescence indicates that it is important to collect fluorescence data between injection cycles rather than simply assuming a background concentration of zero. RWT concentrations are affected only minimally by other fluorescent materials, such as chlorophyll and brighteners, which fluoresce at different wavelengths than RWT [*Smart and Laidlaw*, 1977]. Other factors, however, can influence background RWT readings. False, but very high, background RWT readings were noted during spring of the first year of testing; shielding the sensors from sunlight eliminated the problem, indicating that the sensors may be sensitive to direct sunlight.

[37] Although most RWT plateaus were relatively stable, there were occasional exceptions. The RWT sensors sometimes output data that included spikes in RWT concentration that were not detected by colocated sensors (Figure 4a). Erroneous spikes would cause an underestimate of discharge because the data logger program uses the maximum

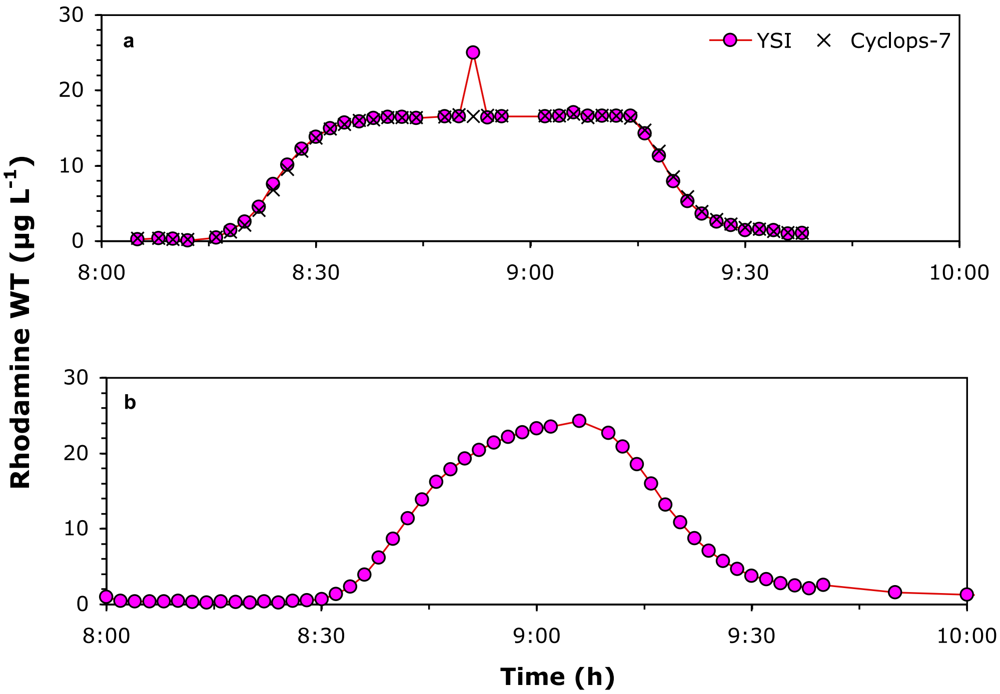

Figure 4. Examples of problems with plateaus in Rhodamine WT concentrations: (a) spike in concentration during plateau and (b) nonsteady state behavior.

RWT concentration during the injection cycle as the plateau concentration. The error normally would be identified and corrected during quality assurance screening; however, a more sophisticated, automated approach to identifying plateau concentrations by the data logger program would be advantageous. Although more computationally intensive, using the maximum of a moving median of RWT concentrations or integrating RWT concentrations under the breakthrough curve would reduce the influence of outliers. Integrating under the breakthrough curve is the method commonly used to calculate discharge using the slug injection tracer dilution technique [*Kilpatrick and Cobb*, 1985].

[38] Another problem can arise if RWT concentrations do not reach a true plateau, as can occur if the injection cycle is not long enough (Figure 4b). If RWT concentrations do not reach steady state, an overestimate of discharge will result. Choosing the length of the injection cycle is an important step during the initial setup of a tracer gauge system and may require some trial and error. Ice damming during spring breakup of in-channel ice caused substantial changes in traveltime during several 2–3-day periods in the spring and was the primary cause of plateaus sometimes not achieving steady state during the study.

3.2. Injection Rate

[39] Injection rate is one of the key variables in the discharge calculation; thus, it is important to quantify and minimize its variability. Fluid level measurements made in the dispensing column indicated minimal variability in the pumping rate during injection cycles (Figure 5). There also was relatively little variability in the injection rates from day to day. During March 2006, for example, the average pumping rate during 93 injection cycles was 0.143 mL s^{-1}, and the relative standard deviation was 1.5%. Thus, the injection system appeared to work reasonably well.

3.3. Rhodamine WT Measurements

[40] The sensor comparison that was performed during February 2006 indicated that the three sensors responded similarly to dye injections. The maximum difference in measured RWT concentrations among the sensors during the plateaus was 5.4% [*Fleming*, 2008]. Although a multipoint calibration was performed on the sensors immediately prior to the experiment, shifts in calibration over time may help explain variations in response. Special attention should be paid to sensor calibration, both during initial setup and routine maintenance.

[41] Calibration errors can be minimized by using the same standards to calibrate the in-stream sensor(s) and the

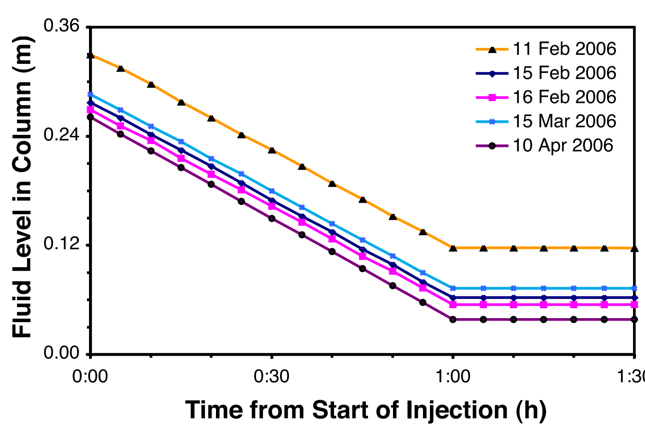

Figure 5. Examples of change in fluid level in dispensing column during dye injection cycles, 2006.

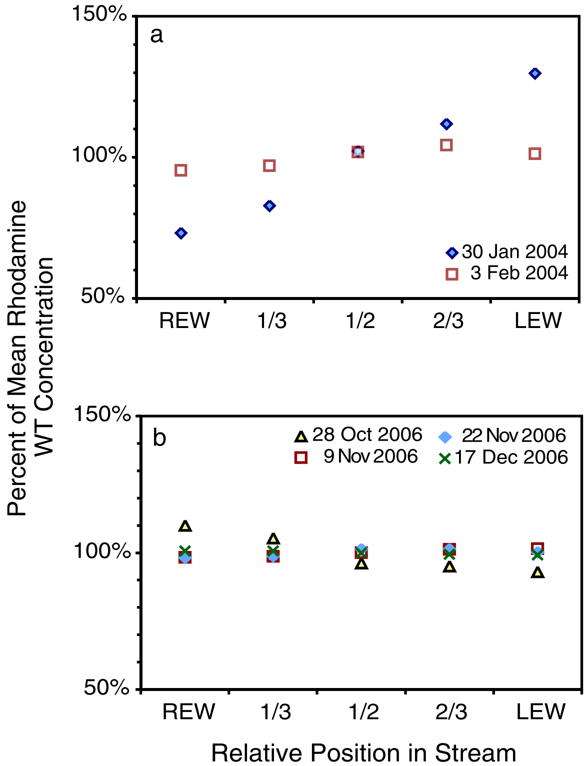

Figure 6. Relative Rhodamine WT concentrations at equal-width increments across (a) Bear Creek (70–90% ice cover) and (b) Fraser River (50–95% ice cover). REW is right edge of water and LEW is left edge of water (looking downstream).

laboratory fluorometer used to analyze the injection solutions. True concentrations are not needed to calculate discharge using the constant-rate dye dilution method because equation (2) relies only on the ratio of RWT concentrations in the injection solution and in the stream. It is, however, important to use RWT from the same lot when making standards and injection solutions because the fluorescence and sorption characteristics of RWT can vary between stock solutions [*Vasudevan et al.*, 2001]. Ideally, standards and injection solutions should be made using stream water from the study site to reduce matrix effects, although in this study a comparison of standards made using distilled water and stream water from the field sites indicated no significant difference ($p < 0.05$). Tap water should be avoided when making standards because chlorine causes degradation of RWT [*Sutton et al.*, 2001].

3.4. Mixing

[42] Mixing at the downstream instrument site at Bear Creek was poor on 30 January 2004 but appeared adequate 4 days later on the basis of the RWT cross-section measurements (Figure 6a). Cold temperatures during the intervening period caused an increase in ice cover from approximately 70% on 30 January to 90% on 4 February. RWT concentrations were much less variable in cross section at the downstream Fraser River site, with all measurements falling within 10% of the mean. Quantitative analysis of mixing at the downstream Fraser River site indicated that it exceeded 97% during each of the four sets of measurements and was better than 99% during three of them (Figure 6b). Ice cover increased from approximately 50% on 28 October 2006 to 95% on 17 December 2006, and mixing tended to be more complete when there was greater ice cover. These results are consistent with observations by *Beltaos* [1998] that in channels with similar friction coefficients spreading of dye was greater in channels with ice than in channels without ice.

[43] Estimated mixing lengths for both sites varied widely, ranging from 30 to 773 m (median = 157 m and mean = 289 m) at Bear Creek and from 32 to 853 m (median = 138 m and mean = 215 m) at the Fraser River [*Fleming*, 2008]. The high variability in estimated mixing lengths suggests that they may be of limited usefulness; actual measurements of mixing based on cross-section measurements while injecting dye at a constant rate can be performed fairly quickly and will be more applicable to the study site.

[44] During the cross-section measurements performed on a longitudinal transect at the Fraser River on 20 October 2007, the degree of mixing varied with distance downstream (Table 2). As expected, mixing was incomplete 30 m below (downstream from) the injection site. Mixing was 99% at 107 m, but it decreased to 84% at 186 m below the injection site, which was just below a large eddy that may not have completely mixed. Mixing was 100% at the three sites 214 m or more from the injection site (Table 2).

[45] Incomplete mixing can be addressed in several ways. The injection and measurement sites could be moved farther apart, but increasing the distance between sites has the disadvantage that the assumption of negligible water gains and losses along the reach may become invalid. Alternatives include using a multiport injection system or using multiple RWT sensors spaced evenly across the stream (as was done at Bear Creek). These approaches may be more expensive but are less likely to invalidate critical assumptions.

3.5. Conservative Behavior

[46] During the cross-section transect test on 20 October 2007, RWT concentrations showed a small but relatively steady decline in a downstream direction (Table 2). RWT concentrations 30 m below the injection site were anomalously low because of incomplete mixing, so those results are not considered further. RWT concentrations at the most downstream site, 317 m below the injection, were 3.5% less than those at the first well-mixed site, 107 m downstream from the injection site. Because of the decrease in RWT, there was a corresponding increase in discharge calculated from the dye dilution measurements (Figure 7a). Manual

Table 2. Mixing and Rhodamine WT Concentration Data From Cross-Section Transect Performed in October 2007[a]

Distance From Injection Site (m)	Percent Mixing	Flow-Weighted Average Rhodamine WT ($\mu g\ L^{-1}$)	Percent Loss of Dye
30	67	7.01	10.8[b]
107	99	7.68	2.1
186	84	7.62	13.9[b]
214	100	7.57	1.9
302	100	7.56	7.6
317	100	7.48	3.5

[a]Ice cover was 20–40%.
[b]Not valid because of incomplete mixing.

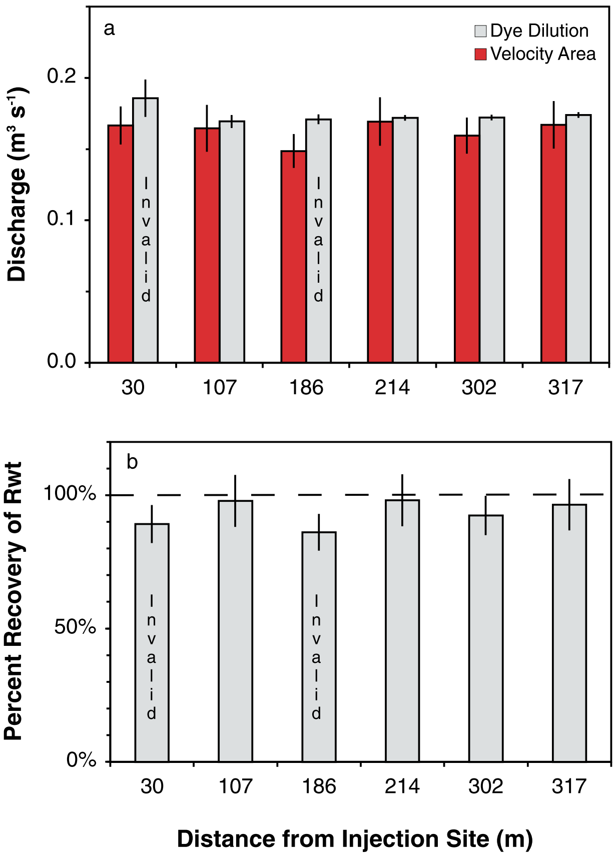

Figure 7. Longitudinal transect on Fraser River of (a) discharge calculated from dye dilution and manual velocity-area measurements and (b) Rhodamine WT (RWT) recovery from mass balance analysis. Ice cover was 20–40%. Whiskers indicate uncertainty in measurements.

velocity-area discharge measurements indicated no statistically significant changes in discharge along the reach on the basis of a Kruskal-Wallis one-way analysis of variance, but the measurements had relatively high uncertainty (±8–10%) because of the roughness of the streambed (Figure 7a). The decrease in RWT concentrations along the reach could be due to adsorption on stream sediments [*Bencala et al.*, 1983], incomplete mixing of dye in the hyporheic zone (transient storage) [*Bencala and Walters*, 1983; *Runkel*, 2002], or exchange of surface water and groundwater.

[47] The shape of the RWT curve can provide insight into the importance of hydrologic processes, such as dispersion and transient storage, during dye injections [*Bencala and Walters*, 1983; *Runkel*, 2002]. Dispersion causes spreading of dissolved substances because of longitudinal advection and lateral mixing [*Beltaos*, 1998]. As a result, changes in RWT concentrations on the rising and falling limbs of the dye breakthrough curve tend to be gradual rather than sharp (Figures 2 and 3). Dispersion should have little effect on discharge calculated using dye dilution methods as long as the injection is of long-enough duration that a plateau occurs. Transient storage in the hyporheic zone or surface water–groundwater exchange, however, could cause an overestimate of discharge because of removal of dye from the stream. Small (1–2%) increases in RWT concentrations during the plateau part of the breakthrough curve indicate that transient storage had a small but discernable effect. Long tails on the breakthrough curve can provide another indication of the effect of transient storage [*Bencala and Walters*, 1983], although they were not observed in this study. Increasing the duration of the injection cycle could reduce the effect of transient storage; however, the potential for improved accuracy needs to be weighed against increased cost of materials and the potential for errors if RWT concentrations do not fully return to background before the next injection cycle.

[48] Surface water–groundwater exchange also can lead to dye loss, but it can be difficult to detect and can alter dye concentrations and mass fluxes in the stream in complex ways that depend on subsurface flow paths. Water leaving the stream along a reach where the dye is well mixed will not change the average stream water dye concentration, but it will decrease the dye mass flux in the stream. Groundwater entering the stream typically will cause stream water dye concentrations to decline, but it will not alter the dye mass flux. Combinations of gains and losses to and from deep subsurface flow paths are possible as well, potentially adding complexity to the dye concentration and flux patterns along a reach. Furthermore, the importance of stream water–groundwater exchange may vary depending on seasonally varying hydrologic conditions [*Gooseff et al.*, 2003]. If maximum accuracy is required for a given study, mass balance analyses should be performed over a range of flows along a longitudinal transect to document how RWT concentrations and fluxes vary with discharge and location along the study reach.

[49] In the present study, mass balance calculations indicate that loss of dye was approximately 3.5% at the most downstream site (Figure 7b), although uncertainty in the velocity-area discharge measurements limits the certitude of the calculations. Because the uncertainty of the velocity-area discharge calculations was greater than the estimated percentage of dye loss, it cannot be known whether the losses were due to dye adsorption of surface water–groundwater exchange.

[50] Site selection should balance the need for complete mixing with the need to minimize the effects of dye loss along the study reach. Longer reaches will promote more complete mixing, but the effects of transient storage and the risk of dye loss from sorption, chemical decay, or water exchange with the subsurface will be greater. These factors need to be weighed to determine the optimum separation distance for tracer dilution discharge measurements.

3.6. Comparison to Reference Discharge Values

[51] Comparison of discharge values from the tracer gauge to those from the Cipoletti weir at Bear Creek indicates generally good agreement (Figures 8a and 8b). The tracer gauge was operated during lower flows and greater ice cover in 2003 than in 2004; together, the 2 years of operation provide data over a broad range of flows and ice conditions. Although ice in the stream channel varied from approximately 20 to 90%, the weir itself was almost always ice free because of high water velocities through the throat. The coefficient of determination (r^2) between discharges calculated from the tracer gauge and discharges from the weir were 0.93 for 2003, 0.94 for 2004, and 0.98 for the combined data set, and all of the regressions were significant at $p < 0.01$ (Figure 9). Differences followed a

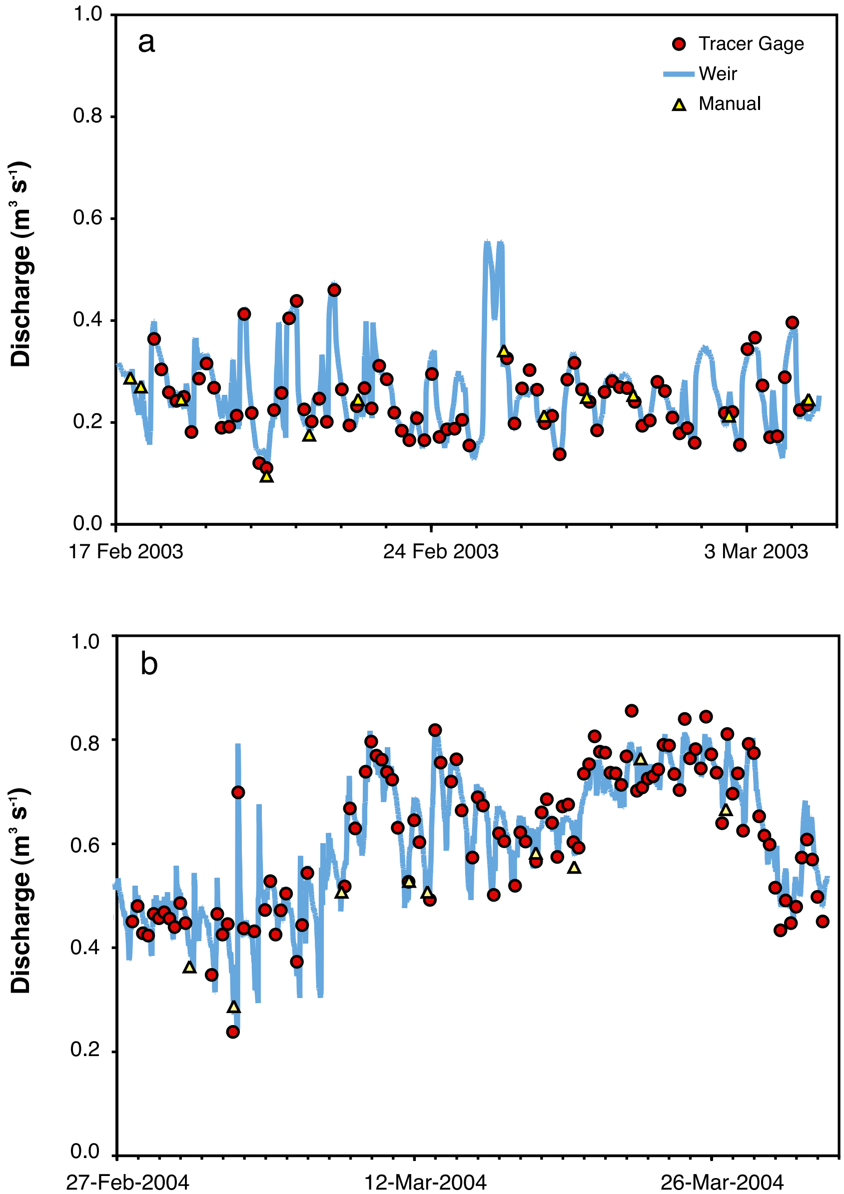

Figure 8. Time series of discharge calculated from the tracer gauge, the Cipoletti weir, and manual measurements at Bear Creek in Morrison, Colorado, during (a) 2003 (60–90% ice cover) and (b) 2004 (20–60% ice cover).

normal distribution, and the root-mean-square error for the combined data set was 0.029 $m^3 s^{-1}$ (1.02 $ft^3 s^{-1}$), which was 6.3% of the mean measured discharge. This provides an estimate of the precision of the tracer gauge system.

[52] A small positive bias is evident in the tracer gauge discharge data from Bear Creek at high flows. The bias primarily affected measurements made during late March 2004, when there was relatively little ice in the channel (Figure 8b). High turbidity associated with snowmelt runoff during that period may have reduced the fluorescence signal measured by the RWT sensors and would increase the likelihood of adsorption of RWT. In study areas with streams that have high turbidity, it would be judicious to monitor turbidity as well as RWT concentrations so that turbidity effects could be accounted for.

[53] Accuracy of Cipoletti weirs generally is ±5% [*Rantz et al.*, 1982], and because differences in discharges calculated from the tracer gauge and the weir were small and normally distributed and exhibited only modest bias, it may be inferred that the tracer gauge has a similar accuracy.

[54] A comparison of discharge values from the tracer gauge to those from the USGS gauge on the Fraser River at Winter Park during winter 2005–2006 illustrates the utility of the tracer gauge compared to the ice-affected records that are normally obtained (Figure 10). Tracer gauge discharge values were relatively steady, as expected under winter base flow conditions, ranging from 0.10 to 0.21 $m^3 s^{-1}$ (3.5 to 7.4 $ft^3 s^{-1}$). Discharge values calculated from 15-min stage readings at the USGS gauge, however, showed numerous spikes and high plateaus (Figure 10). Discharges calculated from the stage data during these times were unreasonably

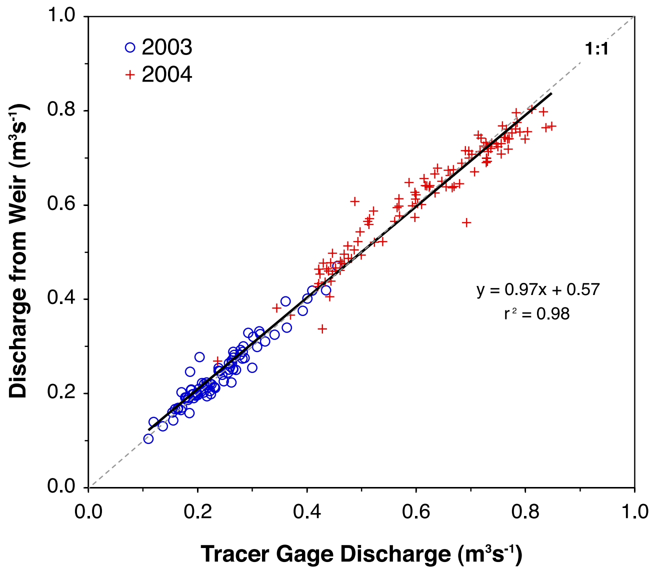

Figure 9. Comparison of discharge calculated from tracer gauge and from Cipoletti weir at Bear Creek at Morrison, Colorado (30–90% ice cover).

high on the basis of visual observations and velocity-area discharge measurements. The spikes in calculated discharge at the USGS gauge coincided with ice jams that caused water to back up in the pool where stage was measured. The high plateaus in calculated discharge were due to the float freezing in the stilling well. It is because of these ice effects that discharge usually is estimated for winter periods in cold regions.

3.7. Error Analysis

[55] The uncertainty in the tracer gauge discharge calculation is a function of uncertainties in measuring the injection rate, concentration of the injection solution, and concentrations of RWT in the stream (equation (2)). The injection rate was quantified on the basis of the change in head of the injection solution in the dispensing column during an injection cycle (Figure 2). The rate of drop in head was relatively steady, indicating that the metering pump delivered dye to the stream at a relatively constant rate (Figure 5). The average drop in head during a 60-min injection cycle was 0.219 m, and the resolution of the pressure transducer was 0.003 m; thus, the uncertainty in injection rate was <1.5%.

[56] The concentration of the injection solution was calculated on the basis of the injection recipe and was validated in the laboratory by analyzing injection solution samples on a high-precision fluorometer. Dilution errors and instrument precision were quantified on the basis of repeating the laboratory dilution and analysis procedures multiple times on samples; results indicated that the combined uncertainty was ≤3% [*Fleming*, 2008].

[57] Uncertainty in the stream water RWT concentration measurements depends on the variability of measured background RWT in the stream and on the resolution of the RWT sensors. Background RWT concentrations were characterized using stream water measurements made prior to the initiation of an injection cycle. Analysis of 27 randomly selected background periods indicated that background RWT concentrations measured by the Cyclops-7 sensor varied by ±0.1 μg L^{-1} (99% confidence interval). On the basis of the observed variability of background measurements and the precision of the sensors, the uncertainty in in-stream RWT concentrations is approximately 1% using the Cyclops-7 sensor.

[58] Incomplete mixing and loss of dye in the stream introduce additional uncertainties in the tracer gauge discharge calculation. As discussed in sections 3.4 and 3.5, at the Fraser River site mixing usually was better than 99%, and loss of dye was 3.5%. If all of the errors described here were cumulative, an error of 11% in calculated discharge would result. If a well-mixed study reach is available and loss of dye is minimal (or can be accounted for), it should be possible to achieve errors of less than 7%, which is consistent with the precision and accuracy estimated for the tracer gauge at Bear Creek.

4. Conclusions

[59] An automated dye dilution stream-gauging system was developed to provide accurate, real-time discharge data for ice-affected streams. The system consisted of instrumentation at two sites separated by a distance sufficient to allow complete mixing of the dye in the stream. Rhodamine WT was injected into the stream at a constant rate using a metering pump, which was controlled by a data logger. The data logger also monitored the injection rate, which is a key parameter in the calculation of discharge. Rhodamine WT concentrations were measured at the downstream site using a submersible fluorometer, and the data were transmitted to the data logger at the upstream site via radiotelemetry. The data logger calculated discharge, which was transmitted via satellite to a Web server, making the data available to water resource managers and the public within 2 h via the Internet.

[60] When setting up a tracer gauge, tests for adequate mixing and conservative behavior of the dye need to be performed to ensure that the assumptions inherent in the constant-rate dye dilution discharge method are met. Inadequate mixing can be caused by too short of a reach between injection and dye measurement locations, and mixing length can vary depending on streamflow and ice conditions. Nonconservative behavior of dye may occur because of adsorption on sediments (especially at low pH), transient storage in the hyporheic zone, or surface water–groundwater exchange along the study reach. Appropriate

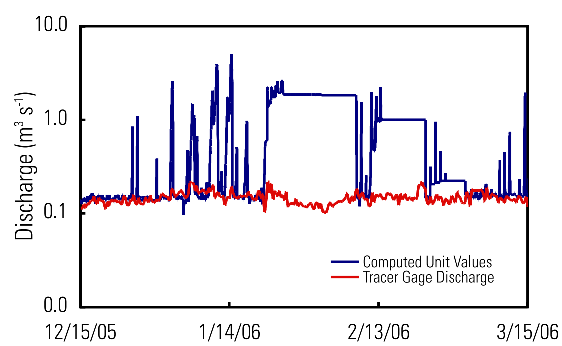

Figure 10. Discharge calculated from tracer gauge and from stage at USGS gauge on Fraser River at Winter Park, Colorado (80–100% ice cover).

tests for mixing and conservative behavior include dye concentration cross-section measurements combined with velocity-area discharge measurements at a number of locations along the reach. Using these data, it is possible to perform a dye mass balance analysis so that dye losses can be quantified within subreaches of the stream. Results at a study site on the Fraser River at Winter Park, Colorado, indicated that mixing was better than 97% (and usually >99%) and losses of dye were 3.5%. Dye losses can be minimized by using the shortest distance that will provide complete mixing between injection and dye measurement sites. Mixing lengths estimated using published equations can vary widely, so performing field tests to establish actual mixing length over the range of expected flows is recommended.

[61] Comparison of discharge values calculated from the tracer gauge and from a Cipoletti weir on Bear Creek in Morrison, Colorado, indicated that the root-mean-square error of the tracer gauge was 0.029 $m^3 s^{-1}$ (1.02 $ft^3 s^{-1}$), or 6.3% of the average measured discharge for the study period. This is consistent with an independent analysis of error on individual system components, which indicated that it should be possible to obtain total error of less than 7%.

[62] Currently, discharge values for ice-affected streams typically have high uncertainty and are estimated between relatively infrequent manual discharge measurements. The tracer gauge has the potential to improve the management of in-stream flow rights during winter by providing accurate, real-time discharge data to water resource managers. These data are needed, but are currently unavailable, for in-stream flow protection programs that are designed to protect fisheries and aquatic ecosystems during periods of low flow.

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